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Atmospheric Environment 38 (2004) 4799–4803

ATMOSPHERIC ENVIRONMENT

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A "test of concept" comparison of aerodynamic and mechanical resuspension mechanisms for particles deposited on field rye grass (*Secale cercele*).—Part 2. Threshold mechanical energies for resuspension particle fluxes

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Received 29 October 2003; received in revised form 17 March 2004; accepted 30 March 2004

Abstract

Kinetic energy from the oscillatory impacts of the grass stalk against a stationary object was measured with a kinetic energy measuring device. These energy inputs were measured as part of a resuspension experiment of uniform latex microspheres deposited on a single rye grass seed pod in a wind tunnel. The experiment was designed to measure resuspension from aerodynamic (viscous and turbulent) mechanisms compared to that from mechanisms from mechanical resuspension resulting from the oscillatory impact of the grass hitting a stationary object. The experiment was run for deposited spherical latex particles with diameters from 2 to 8.1 μm. Wind tunnel tests were run for wind speeds from 2 to 18.5 $m\,s^{-1}$ and a turbulence intensity (root-mean-square fluctuation wind speed/mean wind speed) of 0.1.

Our experiments showed the following:

- Threshold mechanical energy input rates increased from 0.04 to 0.2 $\mu J\,s^{-1}$ for resuspension of spherical polystyrene latex particles from 2 to 8.1 μm diameter.
- Kinetic energy flux generated by mechanical impact of the wind-driven oscillating grass was found to be highly sensitive to slightly different placements and grass morphology.
- The kinetic energy input by impaction of the grass against a stationary cylinder is roughly proportional to the kinetic energy flux of the wind.

Published by Elsevier Ltd.

Keywords: Resuspension; Aerosol; Grass; Wind-tunnel; Aerodynamic

1. Introduction

Resuspension work of Nicholson (1993) suggested that wind-driven resuspension of particles deposited on grass is increased by mechanical disturbances above that caused by purely aerodynamic mechanisms. Aerodynamic mechanisms (A) are direct actions of the turbulent air motions: vibrating of vegetative surfaces, production of sweeping eddies that may detach particles, and viscous forces that remove particles at the mean wind speeds; M mechanisms are mechanical disturbances. Experimentation on rye grass by Gillette et al. (2004)

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1352-2310/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.atmosenv.2004.03.071

Table 1
Descriptions of glass spheres used in the calibration

Name	Size range (μm)	Density	% Round (nominal)	J/sphere (for 1 cm drop)
A-240	2000–2800 (nom)	2.50 (nom)	75	2.9×10^{-6}
A-100	850–1180	2.57	80	1.3×10^{-7}
P-230	500–600	2.45	90	2.3×10^{-8}
P-120	175–275	2.40	90	1.2×10^{-9}
P-060	100–160 (nom)	2.53	90	1.8×10^{-10}

compared resuspension by A mechanisms of oscillating grass in wind with (A + M) resuspension where the M is the impaction of the oscillating grass against an immovable cylinder. Results of this work showed that the (A + M) mechanisms caused more resuspension than the A mechanism alone for polystyrene latex spheres from 2 to 8.1 μm in diameter deposited on grass. Their experimentation measured the wind threshold velocities for A resuspension and proportions of particles resuspended by A mechanisms to (A + M) mechanisms for the same winds.

The goal of this work is to answer the related questions:

(1) What are the thresholds of kinetic energy input for M resuspension?
(2) What is the relationship between the mechanical energy for M resuspension and wind speed?

2. Experimental details

2.1. Measurement of mechanical energy

We used an instrument specifically designed to measure the kinetic energy of impacts that was specially designed instrument to be sensitive below 1 μJ. It was custom built by the Sensit Company of Portland, ND.[1]

Mechanical energy is detected by deformations of a piezoelectric crystal in the instrument and production by the deformed crystal of electrical energy. The electric current generated by the sensor is integrated to represent a sum of impacting energies. When this integration reaches a predetermined value, the integrator is reset, creating one output pulse.

The output of the kinetic energy sensor is a pulse that can be counted by a data logger. The number of pulses produced by the sensor corresponds to the sum of kinetic energies transferred from impactions on the sensor. The amount of kinetic energy required to produce one output pulse is a constant. One output pulse represents the total amount of transferred impacting kinetic energy to the instrument's sensor. An instrument calibration constant converts the output pulse to units of joules per pulse.

An instrument calibration is accomplished by recording instrumental response to known amounts of kinetic energy supplied by impacting glass spheres. Calibration of the kinetic energy sensor was done by dropping glass spheres of known density and diameters onto the active surface of the Sensit sensor at a controlled rate. The kinetic energy of each dropped sphere was calculated by solving for the particle speed V at the sensor (Gillette and Stockton, 1986).

We used glass spheres manufactured by Potters Industries.[1] Table 1 gives the sphere names, size range, density, and percentage round (that is, the fraction of particles that are actually spherical). Values in Table 1 are our measurements except for percentage round or otherwise noted. Diameters of the spheres were measured using a calibrated binocular microscope. Spherical shapes were checked by individual count; the particles were found to be spherical in most cases although some particles were found to be oblong, double spheres, or containing bubbles. Manufacturer's hardness (Knoop 100 g load) values were $515\,\mathrm{kg\,mm^{-2}}$.

2.2. Calibration procedure

The calibration procedure included the measurement of mass of individual glass spheres (A-240 and A-100) or small numbers of glass spheres (P-230, P-120, P-060) to ±0.01 mg. Masses of glass spheres were measured using a Mettler Toledo AT201 Microbalance to ±10 μm. Afterwards, the sphere/s was/were placed onto a glass platform carefully supported at a distance of 1 ± 0.01 cm above the sensitive surface of the device. The sphere was then dropped onto the surface using a razor blade to guide the spheres. If more than one sphere was dropped onto the surface of the device, each sphere had the same speed as it impacted the device because the initial velocity, initial vertical position, and size of each sphere all were the same. As an example of our calibration, the kinetic energy for a 1-cm drop height (expressed as Joules per microsphere) for a 1 cm drop onto the sensor is given in Table 1.

[1] Names of commercial products imply no endorsement by the authors or the US Department of Commerce.

2.3. Calibration results

The response of Sensit instrument 2 versus the kinetic energy of a group of simultaneously dropped impacting glass spheres is shown in Fig. 1. Since all tests were of groups of one or more glass spheres simultaneously dropped 1 cm onto the device, kinetic energy was changed by varying the speed of the spheres and varying the number of identical sized spheres dropped. Speed of the spheres could be changed by varying the height of the drop for drop heights smaller than that for which equilibrium fall velocity is achieved. Fig. 1 shows that there is no response for the P-0060 glass spheres and only a small response for A-240 glass spheres for the drop heights we used. The largest kinetic energy produced by dropping these two sphere types defined the lower limit of our range of sensitivity. Spheres P-230 and P-120 gave responses for the kinetic energies produced by our drop heights that we claim show a linear trend of instrument response to kinetic energy. Finally, Spheres A-100 gave increasing instrumental response with increasing energy, but with a smaller increase of response with increasing energy. We used the kinetic energy value for sphere A-100 drops for which departure from linearity commenced to set the upper limit of our range of detection. The regression line shown in Fig. 1 is for P-230 and P-120 data.

The upper and lower limits of the kinetic energy sensing instrument were 1×10^{-9} and 1×10^{-7} J, and the equation relating number of pulses of the kinetic energy sensor to energy was

$$\text{unit of response} = C*\text{KE}, \tag{1}$$

where $C = 4.33\times10^{7}\,\text{J}^{-1}$ and KE is kinetic energy (J). The standard error for C is $1.2\times10^{6}\,\text{J}^{-1}$. R^2 for the regression was 0.96 with 25 degrees of freedom.

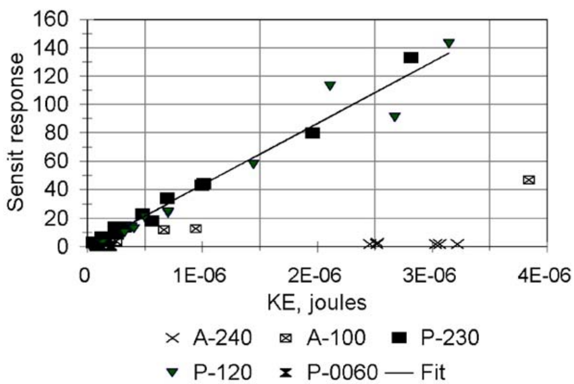

Fig. 1. Response of the kinetic energy sensor to glass spheres dropped from rest 1 cm above the sensitive surface of the Sensit versus the calculated kinetic energy for the spheres at the sensor surface.

2.4. Preliminary tests of the grass kinetic energies that were within the range of the calibration

Grass stalks typical of those used for the experiment were tested to verify that the impacts produced by oscillations against the kinetic energy device produced kinetic energy response within the range of the calibration. Although there were no grass stalks exactly alike, five grass stalks of typical appearance to those used for resuspension measurements gave responses within the range of the calibration from the wind speeds that initiated grass stalk vibration to the top speed of the tunnel. No flattening (saturation) of the response at the high end of the wind speed range (18.5 m s^{-1}) occurred, and the response was smooth with wind speed, consistent with energy transfers that were in the range of the calibration of the sensor.

2.5. Wind tunnel protocol

The kinetic energy measurements were done as part of the wind tunnel tests described in Part 1 (Gillette et al., 2004). Also in Part 1, one can find details on the following: placement of the kinetic energy sensor, the "blank" kinetic energy sensor, placement of the grass stalk, the experimental wind tunnel, and the protocol of the wind tunnel experiments.

During the duration of the experimentation, kinetic energy sensing outputs for the grass-impacted instrument and the background instrument (affected only by noise and vibration of the wind tunnel) the following measurements were recorded every 6 s on the hard drive of a personal computer along with the wind tunnel tachometer reading and particle concentration data. Threshold mechanical energies were estimated to be the lowest mechanical energies for which sustained particle fluxes occur for (A + M) mechanisms and not for A mechanisms alone.

3. Results

3.1. Thresholds for resuspension with and without mechanical impacts of the grass

Thresholds of kinetic energy input rates (μJ s^{-1}) for A&M resuspension were interpolated from the experimental data for all our particle sizes. These quantities given in Table 2 show that thresholds of kinetic energy input increase with particle size from 2 to 8.1 μm. The physical reason for the increase with particle size for wind speed for A mechanisms (see Part 1, Gillette et al., 2004) and with kinetic energy input for (A + M) mechanisms may have to do with the deposition method (painting on a water suspension of the polystyrene latex

Table 2
Threshold kinetic energy for microspheres

Diam (μm)	KE_{thresh} for (A + M) ($\mu J\,s^{-1}$)
2.0	0.04
3.2	0.04
4.5	0.06
8.1	0.2

microspheres) or possibly electrostatic effects with the spheres themselves.

3.2. Relationship between horizontal turbulent flux of kinetic energy and measured mechanical kinetic energy input

An apparent relationship between the horizontal turbulent flux of kinetic energy and our measurement of the 6-s integrated kinetic energy input by the mechanical impacts of the grass stalk against our sensor can be derived for our experimental conditions. As was specified above, the turbulent intensity (see Hinze, 1959) was empirically found to be equal to 0.1. That is

$$\overline{u'^2} = 0.01\,U^2, \tag{2}$$

where U is the mean wind speed of the wind tunnel. The horizontal flux of kinetic turbulent energy is

$$KE_{flux} = 0.5\rho U\overline{u'^2}, \tag{3}$$

By substituting Eq. (2) into Eq. (3) we get

$$KE_{flux} = 0.005\rho U^3. \tag{4}$$

For a 6-s integration period and air density $1.285\,kg\,m^{-3}$,

$$KE_{flux} \times 6\,s = 0.039U^3\ [J\,m^{-2}]. \tag{5}$$

Fig. 2 shows increase of output from the kinetic energy sensor (measuring microjoules integrated for 6-s intervals) times 25 and the integrated 6-s wind tunnel turbulent energy flux from Eq. (5). The factor 25 is simply for comparing the quantities having different units ($J\,m^{-2}$ per 6 s and μJ per 6 s) on the same plot. The kinetic energy sensor output shows great random scatter about the curve described by Eq. (5). The data suggest that the kinetic energy transfer by the oscillating grass to the stationary sensor may be roughly proportional to the wind horizontal turbulent kinetic energy flux.

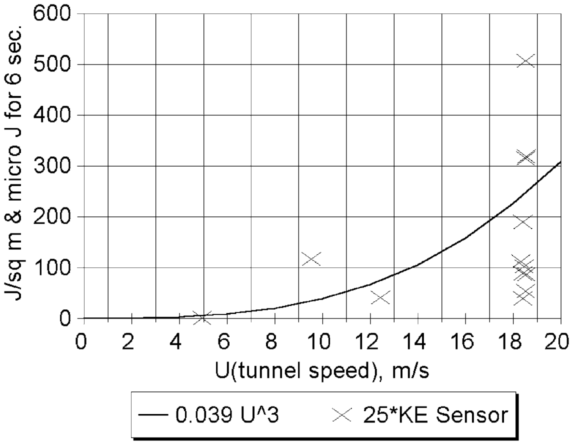

Fig. 2. Output of the kinetic energy sensor per 6-s interval times 25 and 0.039 times the cube of the wind tunnel mean wind speed per 6-s interval versus wind tunnel speed.

4. Discussion and conclusions

Measured mechanical kinetic energy transfers by oscillating grass impaction of the kinetic energy sensor were shown to be highly variable, even though the individual values cluster more-or-less symmetrically about the curve proportional to the cube of mean wind speed. Small displacements of the grass support stand upstream from the kinetic energy sensor at a distance equal to the maximum displacement of the grass head downstream could lead to considerable differences in energy transfer. In addition, the stem diameters and stem-strength (Hooke's constant k of the grass stems) were each slightly different. These small differences probably led to the large variation of kinetic energy shown in Fig. 2.

Our experiments with single stalks of grass can be regarded only as a simplified kind of interaction of grass stalks. However, the increase of the resuspension fluxes caused by the impact of the oscillating grass stalk with a stationary object is consistent with our interpretation that the increase of resuspension of Nicholson's grass surface was caused by mechanical energy transfers by grass blades impacting each other or other objects.

Our experiments showed the following:

- Threshold mechanical energy input rates increased from 0.04 to $0.2\,\mu J\,s^{-1}$ for resuspension of spherical polystyrene latex particles from 2 to 8.1 μm diameters.
- Kinetic energy flux generated by mechanical impacts of the wind-driven oscillating grass for a single wind speed was shown to be highly variable, with a mean roughly proportional to the cube of mean wind speed. The variability for the mechanical impact energies probably arose from slightly different placements and grass morphology. The data suggest that the kinetic energy of grass impacts on the stationary sensor are roughly proportional to the horizontal wind turbulent energy flux and to the cube of the center-line wind tunnel speed.

Acknowledgements

The authors gratefully acknowledge Mr. Ashok Patel, who assisted with much of the laboratory work connected with the experimentation. The authors were partially supported by a US Environmental Protection Agency internal grant U3A026 QT-RT-99-000807. Mr. John Rose designed the grass holder and was helpful in setting up the experiment.

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